

Anisotropic flow generated by hard partons in medium

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Abstract

Hard partons which are produced copiously in nuclear collisions at the LHC, deposit most of their energy and momentum into the surrounding quark-gluon plasma. We show that this generates streams in the plasma and contributes importantly to flow anisotropies. With the help of event-by-event three-dimensional perfect hydrodynamic simulations we calculate the observable azimuthal anisotropies of hadronic distributions and show that the proposed mechanism is capable of generating non-negligible part of the observed signal. Hence, it must be taken into account in quantitative studies in which one tries to extract the values of viscosities from the comparison of simulated results with measured data.

1. Introduction

Expansion of matter excited in ultrarelativistic nuclear collisions provides access to its collective properties: Equation of State and transport coefficients. More detailed study of them is possible if one looks at azimuthal anisotropies of hadron distributions. They are caused by anisotropic expansion of the fireball (for reviews see e.g. [1, 2]).

Indeed, the slope of a transverse-momentum hadron spectrum is influenced by transverse expansion through a Doppler blue-shift. If we

select particles with certain momentum there is a specific part of the expanding fireball which dominates the production of this momentum. Most naturally this would be that part of the fireball which co-moves with the hadrons within our focus. Emission of this momentum from other parts—i.e. those moving in other directions—is suppressed. Thus we have radiating source moving towards the detector. The blue-shift of the radiation is translated into enhanced production of higher p_t . Therefore the spectrum of an expanding source becomes flatter. The range of source velocities co-determines—together with the temperature—the flatness of the spectrum.

If the fireball expands with different velocities in different directions this is usually put into connection with inhomogeneities in the initial state determined by various kinds of fluctuations of energy deposition during the initial impact. By hydrodynamically propagating these inhomogeneities and comparing thus calculated hadron distributions with measured data one tries to determine the properties of matter which enter the evolution model.

One of the problems with this programme is that the initial conditions are only known from various model calculations. Moreover, any other mechanism which influences the flow anisotropies hinders the determination of transport coefficients and must be controlled in good quantitative studies.

We propose here another mechanism which clearly leads to anisotropy in the collective expansion of the fireball. It must be well understood quantitatively if further progress in determination of matter properties is desired.

2. Flow anisotropy from hard partons

In nuclear collisions at collider energies non-negligible part of the energy is initially released in the form of partons with high transverse momentum. At the LHC we have several pairs of partons with transverse momentum above a few GeV per event. Usually, one would refer to them as seeds of minijets and jets. In most cases all of their momentum and energy, however, is transferred into the surrounding quark-gluon-plasma

over some period of time. This creates streams in the bulk which lead to anisotropies in collective expansion.

It is quite conceivable that such a mechanism can lead to flow anisotropies which fluctuate from event to event. Below we will estimate the effect with the help of hydrodynamic simulation. *A priori* it is not clear, however, whether this mechanism is oriented fully randomly or whether it is correlated with the geometry of the collision and also contributes to event-averaged anisotropies.

The latter is the case. Let us first explain how the mechanism works. In a non-central collision the fireball is initially elongated in the direction perpendicular to the reaction plane (which is spanned by the beam direction and the impact parameter). If two dijets are produced and directed both along the reaction plane, they both contribute to the elliptic flow anisotropy, as pictured in Fig. 1 left. Their contribution is positive, be-

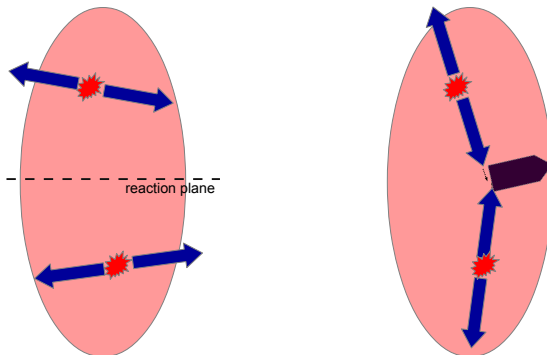


Fig. 1: Left: two dijets produced both almost parallel to the reaction plane. Blue arrows represent generated streams within quark-gluon plasma. Right: Two dijets produced in directions out of reaction plane.

cause due to larger pressure gradient stronger flow usually develops along the reaction plane even without any hard partons. If, however, two hard partons are directed out of the reaction plane, the chance is higher that two jet-induced streams will meet. Then they merge and continue in direction determined by energy and momentum conservation, see Fig. 1. Such a merger is more likely in this case since here the streams pass each

other along the narrow direction of the fireball and have less space to avoid the merger.

Note that via this mechanism isotropically produced hard partons couple to anisotropic shape of the fireball and generate anisotropy of the collective expansion.

An early study mimicking such a mechanism indicated that it will lead to elliptic flow, indeed [3].

3. Hydrodynamic simulations

In order to test our ideas in more realistic simulations we have constructed 3D hydrodynamic model [4]. We assumed perfect fluid. Simulations including viscosity are planned for the future. Note that it is important that the simulation is three-dimensional. Lower-dimensional models assume some kind of symmetry: boost-invariance in case of 2D and additional azimuthal symmetry in case of 1D. Inclusion of hard partons, however, breaks these symmetries and thus full simulation is needed.

Hard partons may deposit large amount of energy into a small volume and its evolution may lead to shock waves. Thus the model must exploit an algorithm capable of handling such a situation. We use SHASTA [5,6].

First we have shown that in a static medium hard partons induce streams which can merge if they come into contact [4].

Then we ran simulations of collisions of Pb nuclei at full LHC energy $\sqrt{s_{NN}} = 5.5$ TeV. Initial energy density profile is smooth and follows from the optical Glauber model. The initial positions of hard partons follow the distribution of binary nucleon-nucleon collisions. Energy and momentum deposition from hard partons into plasma is described as $\partial_\mu T^{\mu\nu} = J^\nu$ with the force term

$$J^\nu = - \sum_i \frac{1}{(2\pi\sigma_i^2)^{\frac{3}{2}}} \exp\left(-\frac{(\vec{x} - \vec{x}_{\text{jet},i})^2}{2\sigma_i^2}\right) \left(\frac{dE_i}{dt}, \frac{d\vec{P}_i}{dt}\right) \quad (1)$$

where the sum runs over all hard partons in the event. We did not study the microscopic mechanism of energy transfer from hard partons to

plasma and only assumed that it is localised within Gaussian distribution with $\sigma_i = 0.3$ fm.

The energy loss per unit of length scales with the entropy density

$$\frac{dE}{dt} \approx c \frac{dE}{dx}, \quad \frac{dE}{dx} = \frac{s}{s_0} \frac{dE}{dx} \bigg|_0 \quad (2)$$

where s_0 corresponds to energy density of 20 GeV/fm³ and $dE/dx|_0$ is a parameter of the simulation for which we tested a few values. Details of the model can be found in [7].

4. Results

Due to flow fluctuations flow anisotropies are generated even in most central collisions. They are observable if one does not average over many events. We first looked at the contribution of our mechanism to anisotropies in central collisions. To this end we simulated 100 central events with included hard partons and then ran THERMINATOR2 [8] five times in order to generate hadrons for each of the obtained freeze-out hypersurfaces.

In Fig. 2 we show 2nd and 3rd order anisotropy coefficients v_2 and v_3 . Results are compared to simulations with no hard partons which indeed show no anisotropies. We studied the dependence on the value of $dE/dx|_0$. Surprisingly results seem not to depend on the particular value of the energy loss. Note that the total amount of the energy deposited into plasma is the same in both cases. They differ by how fast this process runs. The reason may be that in most cases all energy is deposited from hard partons into plasma already at the beginning. We also measure the anisotropies in simulations where hard partons were replaced by hot spots, i.e. local depositions of additional energy density in the initial conditions. They are chosen in such a way that onto the smooth energy density profile the same amount of energy is added as the hard partons would deposit during the whole time. We see that the effect generating flow anisotropies is smaller than with hard partons where also momentum is deposited.

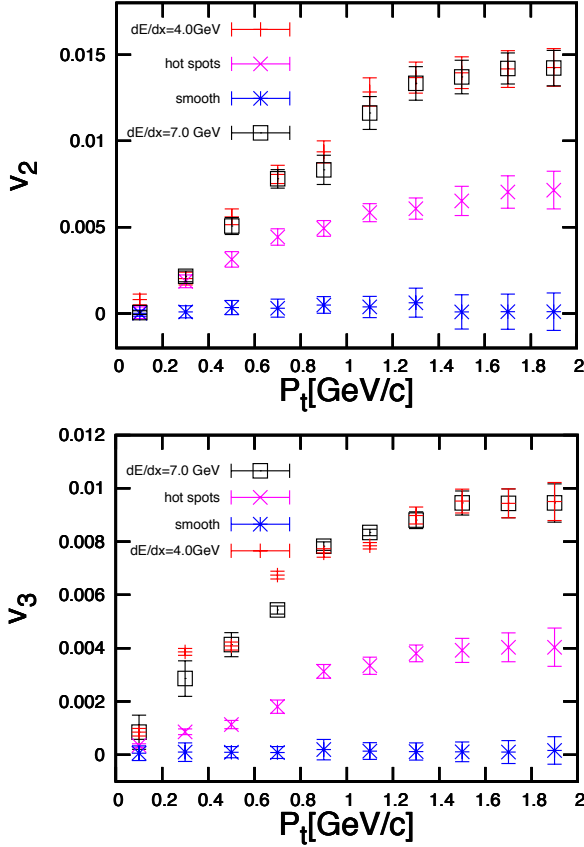


Fig. 2: Top: Second order anisotropy coefficient v_2 of hadronic distributions in ultra-central collisions. Lower data are from simulation with no fluctuations. Upper two sets of data are from simulations with hard partons with different values of $dE/dx|_0$. Crosses in between of these data sets show results from simulations with hot spots instead of hard partons. Bottom: same as top panel but for v_3 .

As a cross-check, we confirmed that no anisotropies of hadron spectra are generated from azimuthally symmetric fireball with smooth initial conditions and no fluctuations.

We also checked how this mechanism is aligned with the geometry in non-central collisions. To this end we simulated fireballs with impact parameter $b = 6.5$ fm and compared anisotropies in cases with or without

hard partons, see Fig. 3. Hard partons indeed enhance the elliptic flow;

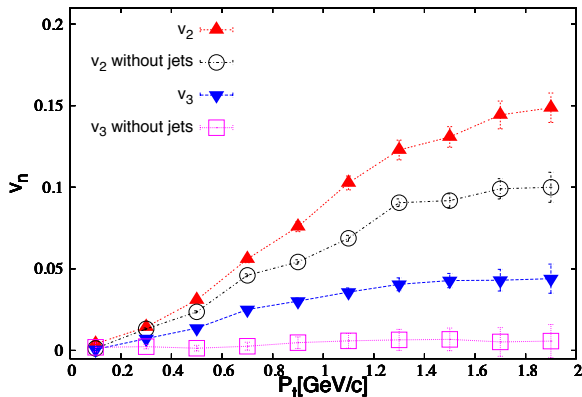


Fig. 3: Azimuthal anisotropy coefficients v_2 and v_3 from simulations of 30-40% centrality class (impact parameter $b = 6.5$ fm). Simulations with hard partons are compared to simulations with only smooth initial conditions and no hard partons (without jets).

this confirms the alignment with collision geometry thanks to merging of the streams. Triangular flow (v_3) is solely generated by hard partons. It is absent in non-central collisions with smooth initial conditions in accord with the symmetry constraints.

5. Conclusions

There are several studies similar to ours documented in the literature.

In [9] the authors study the response of expanding fireball to only one dijet. As we argued previously, this cannot lead to the alignment with the geometry since it is caused by merging of the induced streams.

Simulations in [10] are performed in 2D. We argued that using boost-invariance in this case may be inappropriate.

Finally, in [11,12] the authors only study the influence of hard partons on radial flow and did not touch elliptic flow anisotropies.

Our results show that the contribution to flow anisotropies from hard partons may be relevant in quantitative studies aimed at the determination of the transport coefficients. More precise studies will require

inclusion of three-dimensional viscous hydrodynamic model and other sources of fluctuations.

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